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NUMERICAL SIMULATION OF ASYMMERTICAL DEVELOPMENT OF SANDBARS IN A RIVER MOUTH

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ABSTRACT

In this study, a series of numerical simulations with simple shape of model river mouse is conducted to understand the fundamental mechanism of forces affecting the formation of the sandbars. A coupling scheme of waves, wave induced currents, deformation of bathymetry and river discharge flow is proposed. Incident wave condition is the multi-directional irregular wave, which is closed to real field wave condition. Development of sand bar with bathymetry change is calculated, applying the local sediment transport model proposed by Bailard. Temporal developments of wave, currents, bathymetry change are interacting in the same time step of the numerical program. Configuration of the sandbar is quite sensitive to the direction of wave and currents. Asymmetric development of the sand bar in river mouth is caused by principal wave direction of multi-directional wave.

1. INTRODUCTION

Sandbars in a river mouth often harm discharge flow in a river, eventually increase risks of flood disasters of downriver cities. In Japan, the population is concentrated on the plains adjacent to the coastal area, where people are in danger of flood disaster caused by raising of water surface level in a river mouth, which is refereed to as backwater. Researchers are being continued to study basic mechanics of river mouth or tidal inlet such as described in Suprijo(2004). In river mouth open to the Japan sea (North side of the Japanese Islands shown in Figure 1) sandbars have distinct seasonal cycle of development in winter with seasonal strong winds and severe wave conditions, and its reduction in summer when they have seasonal heavy rain and large discharge flow in river. In the season of large discharge of river, sand bars in river mouth increase of risk of flood. Fundamental understanding of development process of on sandbars and characteristics of its configuration is required for proper management of a river mouth.

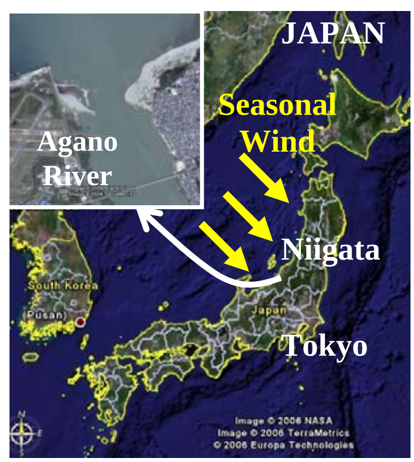

Figure 1 An example of Sandbars in Japan

In Niigata Prefecture in Japan, they had a heavy concentrated downpour on July 13th in 2004. The peak flow discharge of Agano

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river which runs through the central part of Niigata prefecture amounted to 7,700m^3/s. The edge of sandbars of the river mouth was flushed out partly. Figure 2 shows comparison of the sandbars between before or after of the flush. Since the winter in 2004, gradual and asymmetrical development of sandbars from both right and left riverbanks has been observed by the authority of river management in Japan. Waves and wave induced currents are affecting asymmetric development of the sandbars. In general, the shape of the sandbars or coastal errosion is chaotic, which means the interaction of forces on sandbars caused by wave and currents, and the shape of bathymetry in coastal area is quite complicated. Coastal Engineers who are interested in wave and littoral drift proposed numerical model for coastal erosion (Hiraishi (2000)).

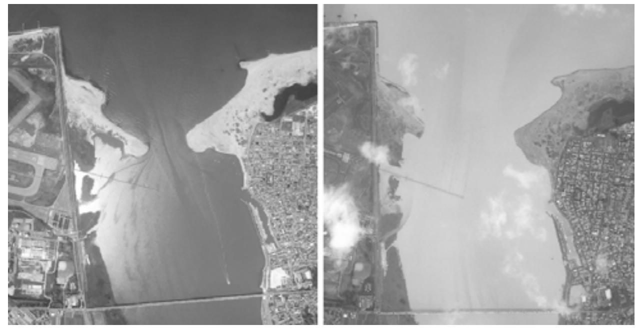

Figure 2 Temporal difference of sand bars
Left：before flood in 2004.5.26
Flood: 2004.07.13
Right：after flood in 2004.7.16
Courtesy of Aganogawa river office (milt)

In this study a series of numerical simulations with simple shape of a model river mouse is conducted to understand the fundamental mechanism of forces affecting the formation of the sandbars. To simulate the complicated phenomena, coupling scheme of wave, wave induced currents, deformation of bathymetry and river discharge flow is used. Incident wave condition for wave height, wave period, wave direction is controlled by the wave-directional spectrum, that is to say, in this study the wave condition is multi-directional and irregular. Wave induced currents for longshore and on-offshore directions are calculated by temporal averaging of instantaneous wave velocities. The deformation of bathymetry is calculated by total budget of sediment transport in each numerical grid. The sediment transport is calculated, applying the local sediment model proposed by Bailard. Temporal changes of wave, currents and bathymetry are interacting in the same time step. With this numerical scheme, interaction of these variables is calculated fully. To calculate wave fields and wave induced near-shore currents, Boussinesq type of wave equation is employed.

2. NUMERICAL PROCEDURE

2.1 Generation multi-directional irregular wave

The incident wave condition of multi-directional irregular wave is generated by following procedure; (1) generation of the directional spectrum as a function of wave condition and hydrographical condition, (2) generating signal of free surface elevation at the boundary of the domain of numerical calculation.

Directional Spectrum $S(f,\theta)$ is available by using wave height observation at many ports in Japan, governed by ministry of land, infrastructure and transportation in Japan. Here, symbols f and θ mean wave frequency and wave direction respectively. It is also available by numerical formulation as multiplication of frequency spectrum $S(f)$ with the wave directional function $G(f,\theta)$. Numerical values of $S(f)$ is given by Bretscheneider-Mitsuyasu spectrum with significant wave height and significant wave period as parameters. Numerical values of $G(f,\theta)$ is calculated by formulation suggested also by Mitsuyasu(1975) in which G is calculated as a function of significant wave period, wind velocity at 10m height from the sea surface, and fetch.

Boundary conditions for the multidirectional irregular wave are defined by assigning value of free surface elevation on the side of the calculation domain. Time series of numerical values for the free surface elevation are calculated by superposing components of each frequency f and each wave direction θ. Detailed method for integration of frequency and direction is described in Hosoyamada(2002). In this study, significant wave period and significant wave height correspond to 9.0s and 2.0m respectively.

2.2 Calculation of wave fields and wave induced coastal currents

To calculate wave fields and wave induced near-shore currents, following Boussinesq equation model is employed. The continuity equation for horizontally two-dimensional wave field, which is derived by integrating incompressible continuity equation associated with free surface kinematic condition is expressed as eq.(1).

$$\frac{\partial \eta}{\partial t} + \frac{\partial Q_x}{\partial x} + \frac{\partial Q_y}{\partial y} = 0 \tag{1}$$

The momentum equations in the horizontal *x* and *y* direction are expressed as eq.(2) and (3) respectively.

$$\frac{\partial Q_x}{\partial t} + \frac{\partial}{\partial x}\left(\frac{Q_x^2}{D}\right) + \frac{\partial}{\partial y}\left(\frac{Q_x Q_y}{D}\right) + gD\frac{\partial \eta}{\partial x} + MD_x = \left(B + \frac{1}{3}\right)h^2 \frac{\partial}{\partial x}\left(\frac{\partial^2 Q_x}{\partial t \partial x} + \frac{\partial^2 Q_y}{\partial t \partial y}\right) + Bgh^3\left(\frac{\partial^3 \eta}{\partial x^3} + \frac{\partial^3 \eta}{\partial x \partial y^2}\right) \tag{2}$$

$$\frac{\partial Q_y}{\partial t} + \frac{\partial}{\partial x}\left(\frac{Q_x Q_y}{D}\right) + \frac{\partial}{\partial y}\left(\frac{Q_y^2}{D}\right) + gD\frac{\partial \eta}{\partial y} + MD_y = \left(B + \frac{1}{3}\right)h^2 \frac{\partial}{\partial y}\left(\frac{\partial^2 Q_x}{\partial t \partial x} + \frac{\partial^2 Q_y}{\partial t \partial y}\right) + Bgh^3\left(\frac{\partial^3 \eta}{\partial y^3} + \frac{\partial^3 \eta}{\partial y \partial x^2}\right) \tag{3}$$

Here, the symbols η, Q_x, Q_y are free surface elevation and depth integrated flow flux in *x* and *y* direction, which are unknown variables in the numerical model. The other symbols *t*, *g*, *h*, *D* are time, gravity acceleration, calm sea depth, total water depth; $\eta+h$. *B* takes constant value 1/21. MD_x and MD_y are wave decay terms for *x*,*y* direction respectively.

In the numerical model, occurrence of wave breaking is judged when the amplitude of flow flux $\hat{Q}$ is larger than the reproduction limitation of wave Q_r. Value for $\hat{Q}$ is calculated in the former time step. When breaking wave occurs, Wave breaking coefficient f_D is calculated by eq.(4) and (5).

$$f_D = \alpha_D s \sqrt{\frac{g}{d}\frac{\hat{Q} - Q_r}{Q_s - Q_r}} \tag{4}$$

$$Q_s = 0.4(0.57 + 5.3s)\sqrt{gd^3},\ Q_r = 0.135\sqrt{gd^3} \tag{5}$$

There are two ways to calculate MD_x and MD_y. One is to calculate momentum decay term directly by multiplication of f_D and Q_x or Q_y. Another way is to use turbulent viscosity, which will be enhanced according to f_D. In this study, the latter way is adopted. The wave decay terms MD_x and MD_y are calculated by eq(6). Turbulent viscosity ν_e is evaluated by eq.(6-1).

$$MD_{x,y} = -\nu_e\left(\frac{\partial^2 Q_{x,y}}{\partial x^2} + \frac{\partial^2 Q_{x,y}}{\partial y^2}\right) \tag{6}$$

$$\nu_e = \begin{cases} \dfrac{gd}{\sigma^2} f_D & f_D > 0 \\ 8 \times 10^{-4}\sqrt{gd}\,\dfrac{d}{s} & f_D = 0 \end{cases} \tag{6-1}$$

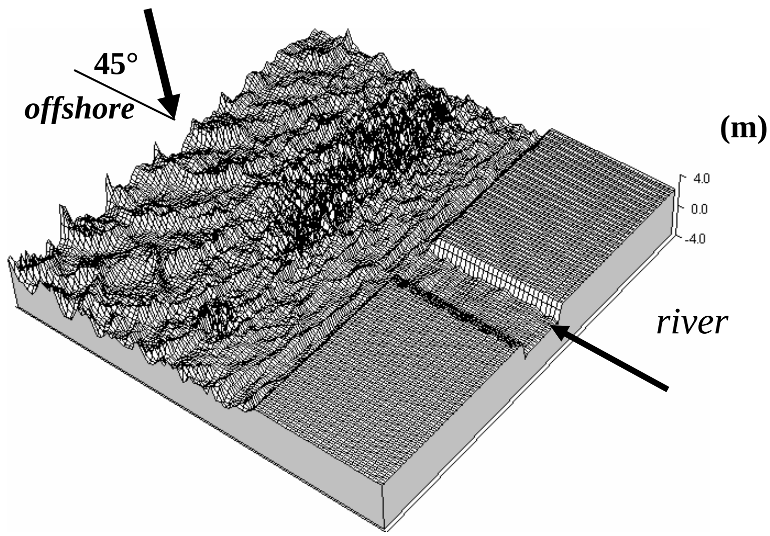

Figure 3 Multi-directional wave fields (bird's eye view)

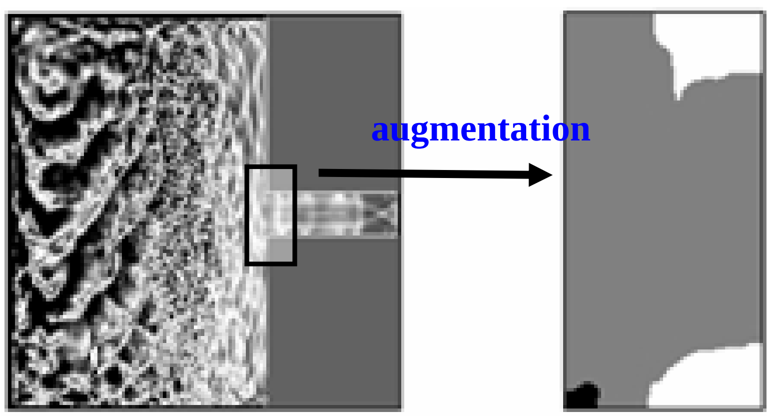

Figure 4 Multi-directional wave fields (left) and development of sandbars at river mouth(right, enlarged image) (plan view)

Wave run-up scheme is also added to the calculation of wave fields. The deformation of sandbars submerged by wave run-up or water level elevation is treated by this numerical model.

2.3 Development of sand bars in the river mouth

Nearshore currents induced by wave breaking and/or nonlinearity of wave motion are calculated by temporal average of the flow velocity associated with the wave propagation. The sediment transport is calculated, applying the local sediment model by Bailard(1981). In the model the change of seabed topography over the passage of time is calculated with eq.(7). The sediment transport flux vector is shown in eq.(8a).

$$\frac{1}{1-\lambda}\frac{dh}{dt} = \nabla\overrightarrow{q_m} \tag{7}$$

$$\overrightarrow{q_m} = \vec{q} + \varepsilon\left|\vec{q}\right|\nabla h \tag{8a}$$

$$\vec{q} = \vec{q}_S + \vec{q}_B \tag{8b}$$

$$\vec{q}_S = \frac{C_f \varepsilon_B}{(\rho_S/\rho - 1) g w_s}\left(\vec{u}_b \left|\vec{u}_b\right|^2 - \frac{\varepsilon_s}{w_s} s \left|\vec{u}_b\right|^3 \vec{i}\right) \tag{8c}$$

$$\vec{q}_B = \frac{C_f \varepsilon_B}{(\rho_S/\rho - 1)\tan\phi}\left(\vec{u}_b \left|\vec{u}_b\right|^3 - \frac{s}{\tan\phi}\left|\vec{u}_b\right|^5 \vec{i}\right) \tag{8d}$$

The subscripts B and S in eq.(8b) denote the bed material load and suspended load respectively, which are calculated by (8c) and (8d) respectively. Definition of the symbol ρ_s, c_f, ϕ, u_b, w_s, λ are density of sand, drag coefficient of bed, angle of internal friction, sinking velocity of sediment, void ratio of sediment respectively. Other symbols ε, ε_S, ε_b are adjustable coefficients. Concrete values of these parameters are same as Hosoyamada(2002).

3 NUMERICALRESULTS AND COMPARISON WITH AGANO RIVER MOUTH

3.1 Numerical results

Figure 3 shows a snapshot of multi-directional irregular wave fields with principal wave direction of 45 degree. Wave breaker zone is shown in front of the river mouth. In offshore region of the calculation domain, waves have multi-directional character. In nearshore region, wave has uni-directional character owing to wave refraction.

Figure 4 shows a plan view of instantaneous surface water elevation and a plan view of argumentation of the deformation of sandbars. Configuration of the sandbar is asymmetric due to the asymmetric manner of incident wave and wave induced currents. Development of asymmetric sandbars is due to asymmetric character of wave direction of incident wave. This numerical study shows fundamental mechanism of formation of asymmetric sandbars clearly.

Wave induced currents at sea bed are calculated with multiplication of temporal average of instantaneous wave induced current and vertical transfer function of wave. Spatial distribution of the current vector in case incident wave angle is 0 degree. is shown in figure 5. In the vicinity of the offshore side of the river mouth, currents show complicated circulation. Some circulations have strong longshore direction. Run up currents into the river are quite remarkable as the incident wave direction is just opposite to the downstream direction of the river.

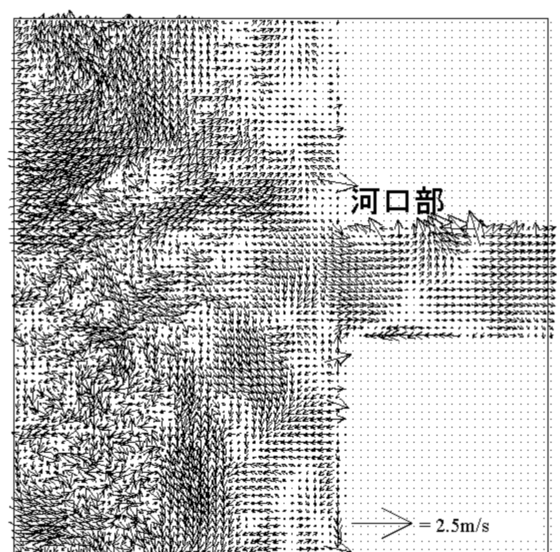

Figure5 Bottom velocity vectors of coastal currents Temporal average is taken for significant wave period. Incident wave direction : 0 degree

3.2 Dependence of formation of sandbars on principal wave direction

Figure 6 shows horizontal distribution of generated multi-directional irregular waves. In each figure, onshore direction is from left top to right down, while longshore direction is just perpendicular to the direction. The figures are arranged in the order of principal wave direction. In each figure, crest line of the wave is almost perpendicular to principal wave direction which is shown in each figure by number. At the center of the calculation domain, wave is fluctuating remarkably because of wave breaking. Waves are stably progressive after passing through the breaker zone. Wave direction is close to normal direction to coastline because of the wave refraction. Wave run-up is shown in the river region just situated between the lands region. In the three cases, wave run-up height increases as the principal wave direction is closer to the normal direction to the coastline, that is to say the incident wave angle is close to 0 degree. Area of wave breaker zone increases as increase of the incident wave angle. Wave refraction is shown as motion of wave crest line in Animation.

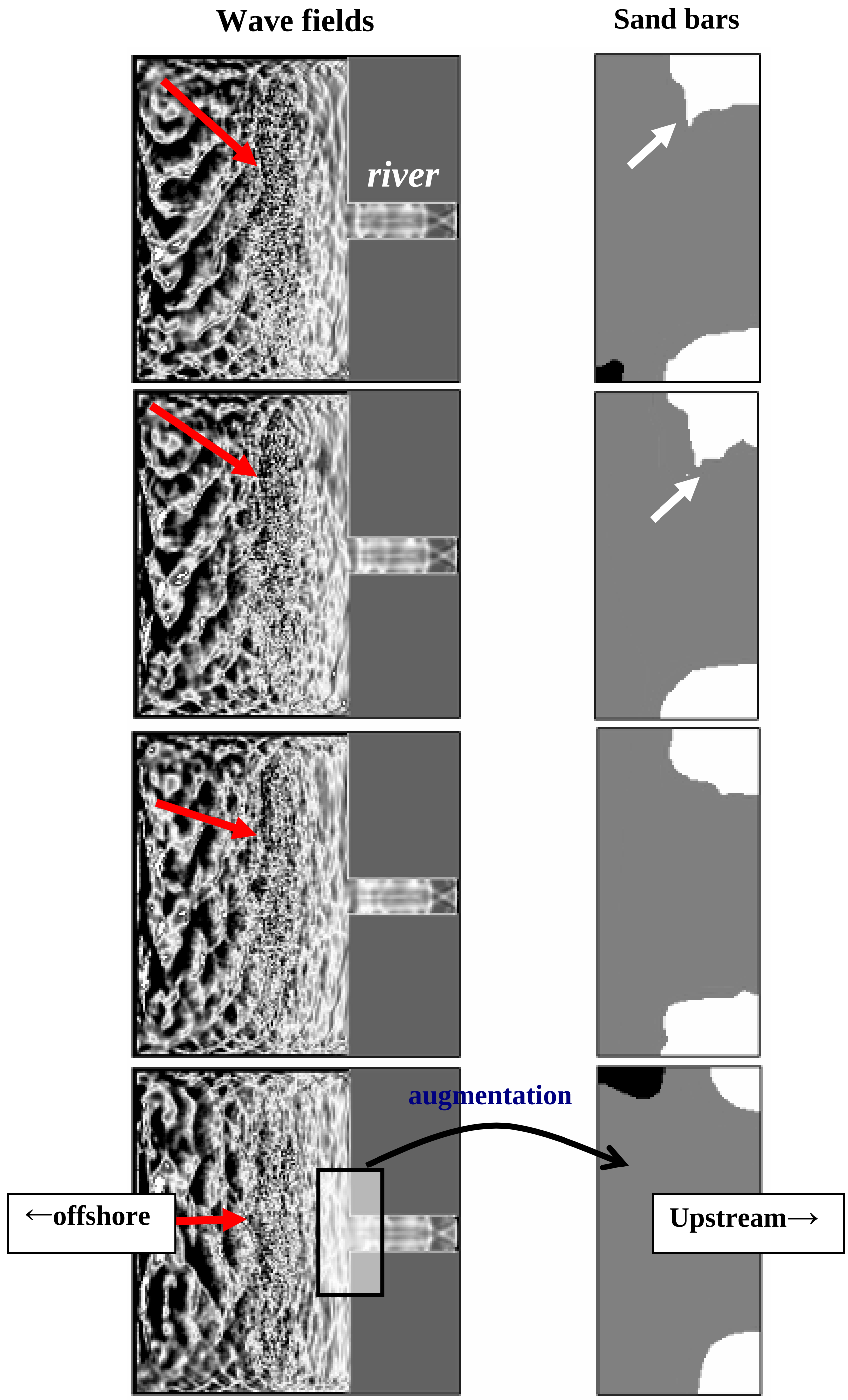

Figure.6 Wave fields and deformation of sand bars
Principal wave direction from above 45,30,15,0degree

In Figure 7, a series of numerical results for wave and deformation of bathymetry in the river mouth are shown in the order of principal wave direction of incident wave. In the offshore region where incident wave condition for multi-directional irregular wave is given, wave condition is highly multi-directional, whereas wave is close to uni-directional in near region because of wave refraction. Deformation of bathymetry is quite sensitive to the change of incident wave direction especially in the river mouth. For the case of incident wave direction 45 and 30 degree longshore currents are enhanced and sand bars extends downstream direction of the coastal currents as pointed out by white arrow in the figure. For the case of principal wave direction 15 or 0 degree, the littoral drift is forced in the river and finally bars develop symmetrically with respect to channel of the river.

3.3 Comparison with fields

Wave observation nearest to Agano river mouth is conducted at offshore site of Niigata port as operation of ministry of land,infrastructure and transportation(milt) of Japan. The dataset is stored as NOWPHAS(Nationwide ocean wave information network for ports and harbours) which is available through Coastal Development Institute of Technology (CDIT) in Japan. In the statistical analysis of the wave data of NOWPHAS, principal wave direction corresponds to -30degree in this numerical simulation domain. In the real field, direction of coastal currents agrees with principal wave direction. In Agano river mouth, sandbar in the left side of the river flow is comparatively stronger than the right side. In this numerical study, principal wave direction takes positive value, which means numerical works and real fields are symmetrical with respect to the river flow. Numerical results of asymmetrical development of sandbars show qualitative agreement with real field observation in consideration of difference of principal wave direction.

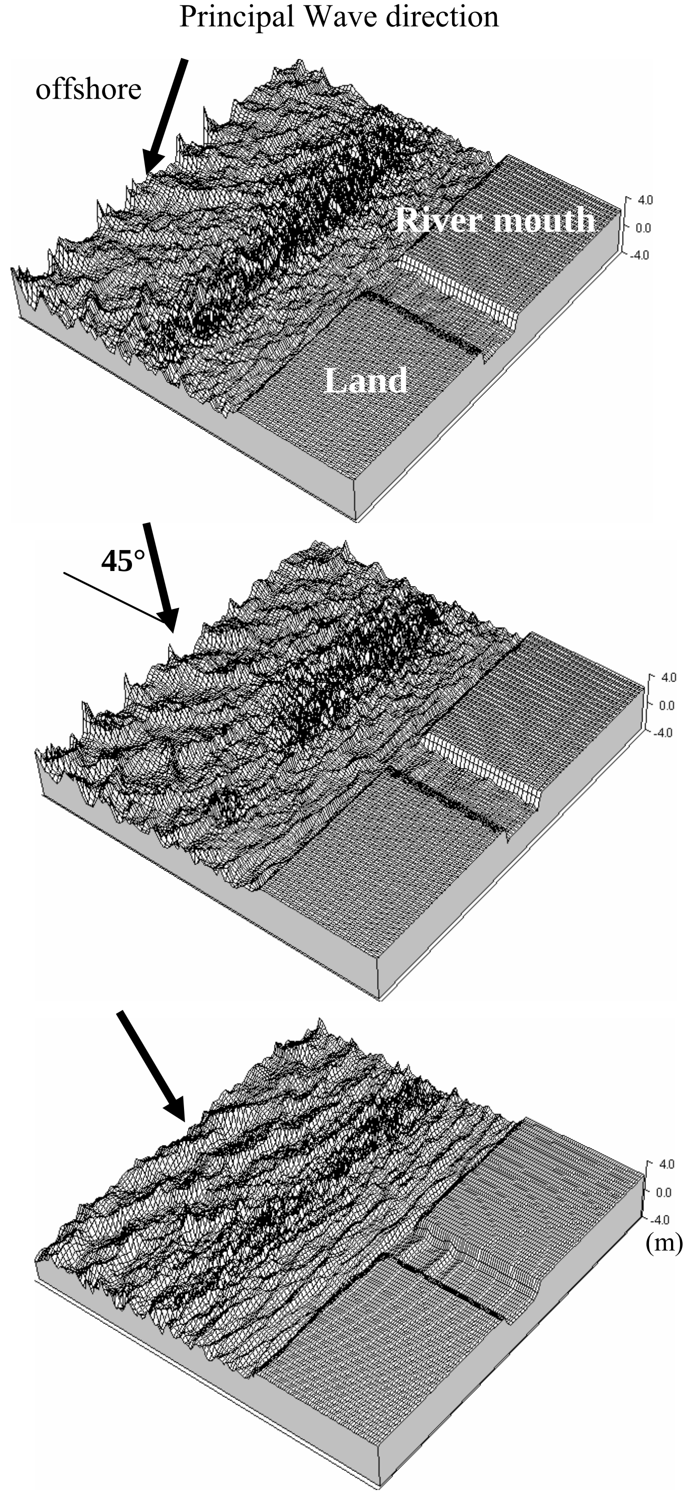

Figure 7 Wave Propagation for each wave direction
Incident wave direction 75°,45°,15°

4 CONCLUSION

In this numerical study of interaction of multi-directional wave, wave induced currents, sand drift and bathymetrical change we are successful in reproducing symmetrical development of sandbars. For the case of principal wave direction 0 to 15degree, sand bar dose not develop asymmetrically, whereas for the case of more than 30degree, sand bars go with the coastal currents and develop asymmetrically.

In this paper, we showed qualitative agreement of development of sandbar in river mouth. In the future, we will conduct a qualitative study which includes change of vertical thickness of the sand bars using field scale calculation domain.

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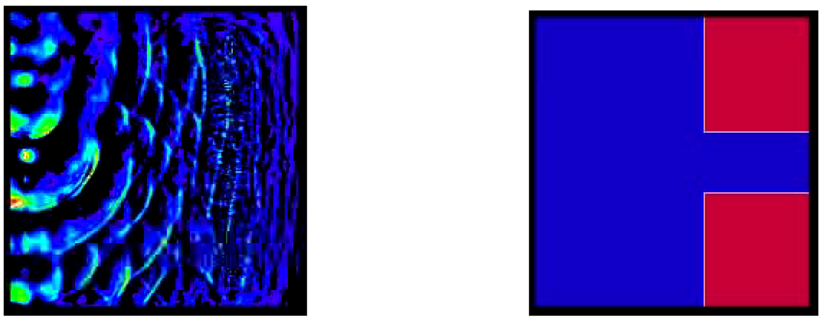
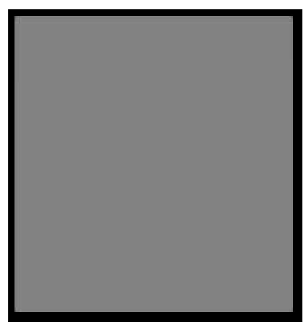
APPENDIX

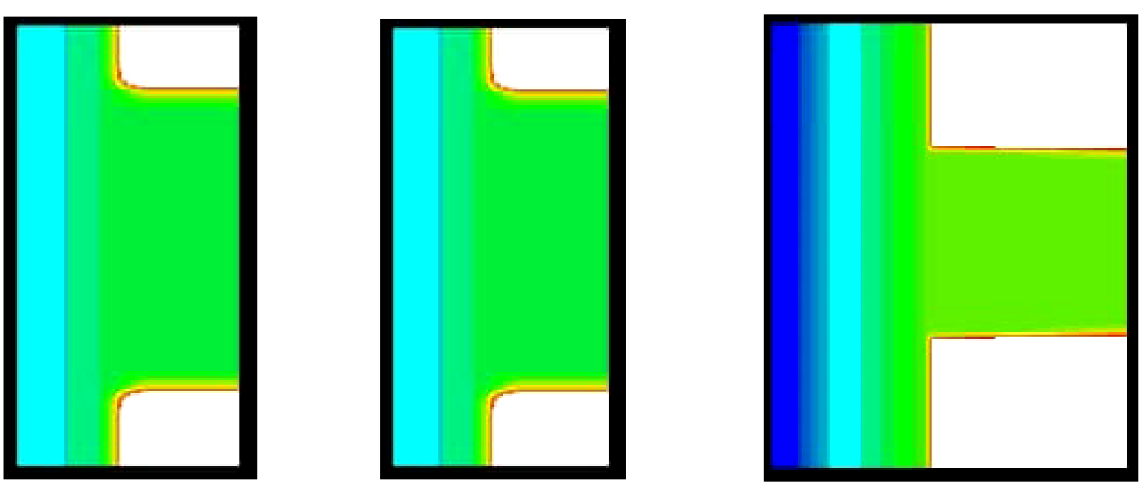
Now a days, most of numerical studies in hydraulics are examined by seeing animation because research object of hydraulics is almost always moving. Here in this appendix of the paper, wave propagation, wave breaker and deformation of sand bar is given by animation files.
Author's environment for edition of this paper: *MicroSoft Windows* XP SP2, *MicroSoft Word* 2003, *Adobe Acrobat* 7.0 Professional. Format of animation files is mpeg2. To see the animation, please click on each figure. A window for your approval of animation may come out. Please click "OK".
For each animation, left and right side are offshore and onshore direction respectively.
A1) **an example of wave propagation of multi-directional wave**: left: general image, right: river mouth with principal wave direction 45degree



A2) **distribution of wave breaker coefficient f_D near the river mouth**



A3) **temporal change of sandbars**: left: principal wave direction 15 degree, center:45 degree, right: final development of sandbars 45 degree.



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